Nuclear interference effects in ^{8}B sub-Coulomb breakup

F.M. Nunes[1]
Departamento de Física, CENTRA, Instituto Superior Técnico,
Av. Rovisco Pais, 1096 Lisboa, Portugal.

I. J. Thompson
Department of Physics, University of Surrey, Guildford GU2 5XH, UK

Abstract

The breakup of ^{8}B on ^{58}Ni below the Coulomb barrier was measured recently with the aim of determining the Coulomb breakup components. We reexamine this reaction, and perform one step quantum-mechanical calculations that include E1, E2 and nuclear contributions. We show that the nuclear contribution is by no means negligible at the intermediate angular range where data was taken. Our results indicate that, for an accurate description of this reaction, Coulomb E1, E2 and nuclear processes all have to be taken into account.

In order to understand the details of Coulomb breakup experiments of ^{8}B on heavy targets [1, 2], and to extract an S_{17} for astrophysical relative $p+^{7}$Be energies from the measured Coulomb Dissociation (CD) cross sections, it is necessary to know the relative importance of the E1 and E2 Coulomb contributions to breakup. The Notre Dame experiment on the Coulomb dissociation of ^{8}B on ^{58}Ni at 26 MeV [3] therefore sought to determine these contributions by measuring the integrated cross section of the ^{7}Be fragment between 39° and 51°. At these much lower beam energies the E2 should be as large (or larger) than the E1 contribution, and so a measurement of the total breakup probability should give strong constraints on both the integrated B(E1) and B(E2) transition strengths. Since the closest distance of approach at 26 MeV for the above angles is 15 fm, and plausible optical potentials give elastic $\sigma/\sigma_R < 0.5$ only beyond 90°, it was believed that the E1 and E2 contributions could be measured free from nuclear effects with the Notre Dame setup.

However, the results of the Notre Dame experiment [3] disagreed [4, 5] with the theoretical predictions for a variety of structure models of ^{8}B ([6, 7]), when using the standard semiclassical theory of Coulomb excitation [8]. The predictions of the semiclassical breakup theory were twice or three times the measured cross section. This discrepancy raises some fundamental questions: How strong is the dependence of the CD cross section on structure model of ^{8}B? Should nuclear effects be taken into account? How important are interference terms: Coulomb-Coulomb, nuclear-nuclear and Coulomb-nuclear? In ref. [5] it is shown that no remotely-reasonable structure model could give a breakup probability as small as that measured in [3]. This work answers the second question on nuclear contributions, and hints on a possible answer to the third question on multistep effects.

[1]Email address: filomena@wotan.ist.utl.pt

In order to examine the validity of the semiclassical approximations previously used in [3, 4], we performed quantum-mechanical calculations of the single-proton excitations from a ground state to a range of continuum states. We discretise the continuum by the method of continuum bins, as used in the CDCC methods reviewed in ref. [9]. Since, however, results using this method for Coulomb transitions have been attempted [10], but not yet fully demonstrated [11] to be converged, especially for E1 transitions, we confine ourselves to dipole and quadrupole transitions only to and from the ground state to the continuum, and omit the couplings between continuum states. We hence perform first-order distorted-wave Born approximations to the full CDCC problem, but report on these DWBA results because these immediately lead us to see some severe short-comings of the previous applications of semiclassical methods.

We therefore perform prior-DWBA breakup calculations by discretising the continuum with $s_{1/2}$, $p_{1/2}$, $p_{3/2}$, $d_{3/2}$, $d_{5/2}$ partial waves up to E(p-^{7}Be)$=3$ MeV. We have taken a single particle model for the structure of ^{8}B assuming that all states in ^{8}B are determined by the g.s. potential defined in [7] (this simplification of the ^{7}Be-p scattering state interaction has hardly any effect on the integrated Coulomb Dissociation cross section [5]). For the continuum discretisation, good accuracy is obtained if we use 13 bins defined in the following way: 9 bins of 100 keV centred at $0.15; 0.25; ...; 0.95$ MeV and 4 bins of 500 keV centred at 1.25; 1.75; 2.25; 2.75 MeV. In order to obtain convergence for the E1 and E2 transitions we include up to $l_{max} = 600\hbar$ and $R_{max} = 300$ fm for the reaction mechanism, in the code FRESCO [12].

We first check that we reproduce the pure Coulomb semiclassical results for E1 and E2 excitations under the same physical approximations. This requires that we use the pure $r^{-\lambda-1}$ shapes for the Coulomb multipoles, which would be true for a point projectile. The comparison of the semiclassical and quantum mechanical differential cross section as a function of the ^{8}B scattering angle is shown by the circles and long-dashed lines in fig.(1) and the agreement is perfect. This indicates that the continuum energy range has been discretised with sufficient accuracy for at least the one-step treatment of this reaction.

In fig.(1) the dot-dashed line shows the pure Coulomb result obtained by folding the projectile-target interaction with a ^{8}B wavefunction of a realistic size (the ^{7}Be-p interaction given by [7]). Due to the long tail in the ^{8}B g.s. wavefunction (the binding energy is only 0.137 MeV) we find that the point-projectile approximation is not valid for angles larger than $20°$. The simple condition $b > R_p + R_T$ assumed in applying the semiclassical Alder and Winther theory is not valid when the projectile has such an extended nature.

We next calculate the pure nuclear differential cross section (short-dashed line in fig. 1). We use a Becchetti-Greenlees p-^{58}Ni potential [13] at 3 MeV, and we take, for the ^{7}Be-^{58}Ni, the optical potential from [14] which was extracted from ^{7}Li scattering on ^{58}Ni at 34 MeV. These potentials, with their Coulomb parts, are both used in folding integrals to find dipole and quadrupole transitions from the ground state. They are also folded to obtain the rather

diffuse monopole potentials which govern the c.m. motion of the excited ^{8}B* states in the exit channels. We find (fig. 1) that the nuclear contribution is insignificant up to 20°, but grows rapidly beyond that, peaking at $\simeq 70^\circ$.

When nuclear and Coulomb multipoles are included coherently (solid line in fig.1), there are already small effects below 20°, a pronounced Coulomb-nuclear interference minimum between 25° and 50°, and a nuclear-dominated peak at $\simeq 70^\circ$. This large nuclear effect is present even though the elastic Coulomb + nuclear cross section drops only to 90% of the Rutherford cross section at 70°, because of the large halo-like size of proton wavefunction in the g.s. of ^{8}B. The dip in the differential cross section coincides with the angular range measured in the Notre Dame experiment, suggesting that including nuclear effects is at least part of the solution to the disagreement between semiclassical predictions and data. Our calculations of the nuclear effects are qualitatively similar to the results in [15], where Coulomb and nuclear effects are also calculated by folding single-particle potentials over the wave functions of discretised continuum states. In [15], however, the ^{7}Be$+^{58}$Ni potential is omitted from the transition operator, and the excitation mechanisms are determined by integrating along a semiclassical trajectory determined by a fixed ^{8}B + ^{58}Ni optical potential.

In fig.(2) we show the separate dipole and quadrupole contributions to the differential cross section for the pure Coulomb process (with finite ^{8}B size) as well as for the case when nuclear is also included. The dipole to quadrupole ratio around 45° (the angular range corresponding to the Notre Dame data) can change considerably by including the nuclear contribution. The quadrupole response is proportionately more affected by the nuclear interference in the middle range of angles $15^\circ - 50^\circ$.

Finally, in order to illustrate the sensitivity of the breakup cross section to the optical potentials, we compare in fig.(3) the results using two different sets of parameters both extracted from ^{7}Li scattering data: nuclear1 from [14] at 34 MeV and nuclear2 from [16] at 14.2 MeV. For these calculations we have also included the relative f-waves in the ^{8}B continuum, which increases the cross section because of additional E2 contributions. Up to 50° the differential cross section is unaffected, while there are large differences around the nuclear peak. We also show the effect of including only the real part of the $p+^{58}$Ni potential and neglecting the ^{7}Be$+^{58}$Ni potential altogether (nuclear3). We see that the $p+^{58}$Ni potential is responsible for the largest part of the interference effects between 15° and 50°. Fortunately, this potential is experimentally well-determined as compared with the ^{7}Be potential.

Other authors have pointed out the importance of higher order Coulomb-Coulomb effects for the ^{8}B breakup in the intermediate energy regime [7]. One should keep in mind that our conclusions are based on 1-step distorted-wave coupled continuum bins calculations. It is clear from fig.(1) that Coulomb-nuclear interference becomes considerable for angles above 20°. Given the strength of the nuclear peak we would expect multiple step processes to play an important role. More work on these lines is underway and will be reported in the near future.

The initial objective of the Notre Dame experiment was to measure the magnitude of the E2 component in the CD of ^{8}B in order to determine the smaller E2 effects in the forward angle experiments performed at higher energy, where the process is E1 dominated [1, 2]. This low-energy effort becomes increasingly hard when nuclear effects and multistep processes are mixed in. For the unambiguous extraction of E1 and E2 Coulomb amplitudes from breakup experiments, the large extent of the ^{8}B g.s. wave function requires measurements at 3 MeV/A to be performed at angles of 15° or more forward. This corresponds to a distance of closest approach of 40 fm or more. For closer collisions, we find that nuclear effects cannot be avoided. Furthermore, more conclusive results from the Notre Dame experiment will only be possible after multistep processes have been fully analysed.

We thank Andrea Vitturi for fruitful discussions. UK support from the EPSRC grants GR/J/95867 and Portuguese support from JNICT PRAXIS/PCEX/P/FIS/4/96 are acknowledged. One of the authors, F. Nunes, was supported by JNICT BIC 1481.

References

[1] T. Motobayashi et al., Phys. Rev. Letts. **73** (1994) 2680

[2] T. Kikuchi et al., Phys. Letts. **B391** (1997) 261

[3] Johannes von Schwarzenberg et al., Phys. Rev. **C53** (1996) R2598

[4] R. Shyam and I.J. Thompson, Phys. Letts. **B415** (1997) 315

[5] F. M. Nunes, R. Shyam, I.J. Thompson, Proc. *International Workshop on Physics with Radioactive Nuclear Beams*, Puri, India, January 12 - 17, 1998, submitted to J. Phys. G.

[6] K.H. Kim, M.H. Park and B.T. Kim, Phys. Rev. **C53** (1987) 363

[7] H. Esbensen and G. Bertsch, Nucl. Phys. **A600** (1996) 37

[8] K. Alder and A. Winther, *Electromagnetic Excitation*, (North Holland, Amsterdam, 1975)

[9] Y. Sakuragi, M. Yahiro and M. Kamimura, Prog. Theo. Phys. Suppl. **89** (1986) 136

[10] Y. Hirabayashi and Y. Sakuragi, Phys. Rev. Lett. **69** (1992) 1892

[11] G. Baur and H. Rebel, J. Phys. G **20** (1994) 1

[12] I.J. Thompson, Computer Physics Reports, **7** (1988) 167

[13] F.D. Becchetti and G.W. Greenlees, Phys. Rev. **182** (1969) 1190

[14] C.W. Glover, R.I. Cutler and K.W. Kemper, Nucl. Phys. **A 341** (1980) 137

[15] C.H. Dasso, S.M. Lenzi and A. Vitturi, submitted to Nucl. Phys. A

[16] Z. Moroz et al., Nucl. Phys. **A 381** (1982) 294

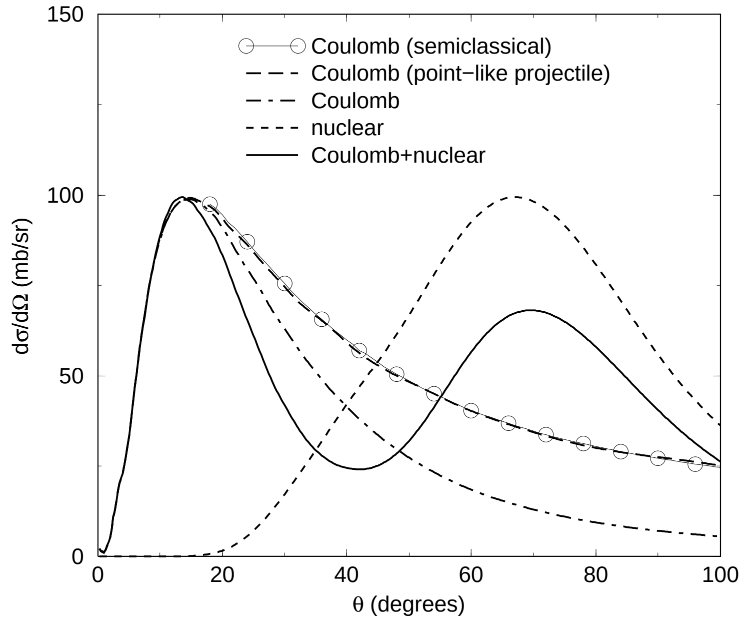

Figure 1: Comparison of the Coulomb and the nuclear contributions to the differential cross section for the breakup of ^{8}B on ^{58}Ni in the Notre Dame experiment [3].

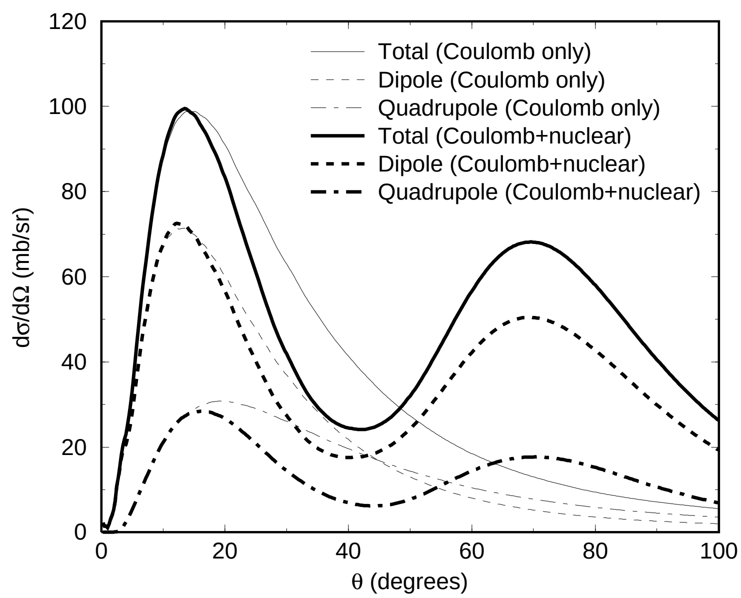

Figure 2: The dipole and quadrupole components of the differential cross section for the breakup of ^{8}B on ^{58}Ni with and without the nuclear interactions with the target.

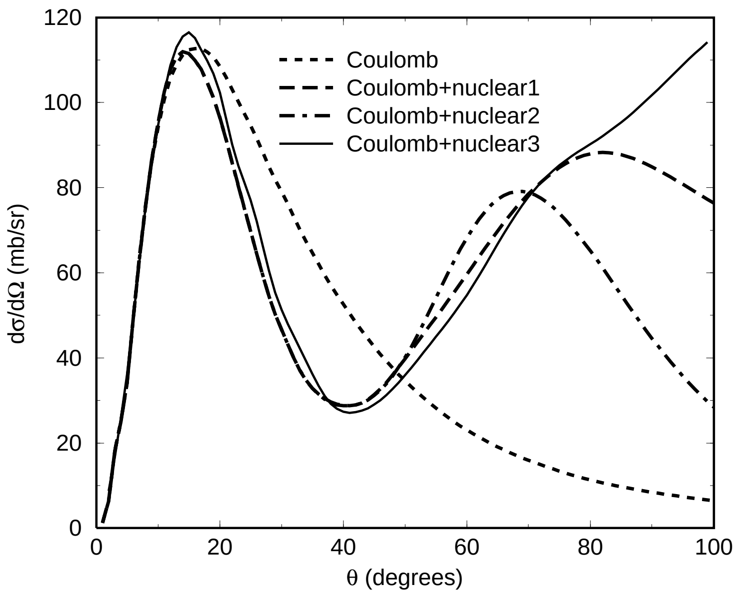

Figure 3: The sensitivity of the differential $^{8}B^{*}$ breakup cross section to the ^{7}Be-target nuclear interaction.